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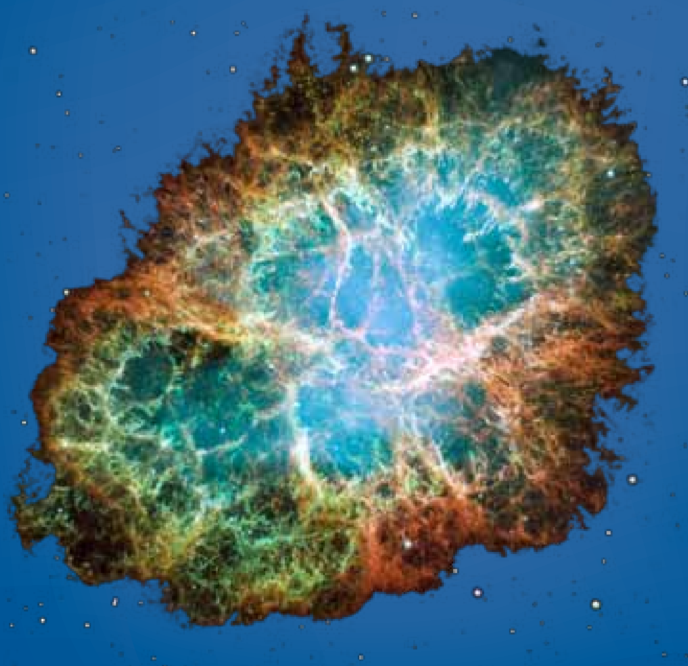
Experiencing Hubble: Understanding the Greatest Images of the Universe

Course Guidebook

Professor David M. Meyer
Northwestern University



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Professor David M. Meyer is Professor of Physics and Astronomy, director of Dearborn Observatory, and co-director of the Center for Interdisciplinary Exploration and Research in Astrophysics at Northwestern University. He received his B.S. in Astrophysics at the University of Wisconsin–Madison after completing a senior honors thesis on ultraviolet interstellar extinction with Professor Blair Savage. Professor Meyer earned his M.A . and Ph.D. in Astronomy at the University of California, Los Angeles, working with Professor Michael Jura on measurements of the cosmic microwave background radiation from observations of interstellar cyanogen. He continued his studies as a Robert R. McCormick Postdoctoral Fellow at the University of Chicago's Enrico Fermi Institute before joining the Northwestern faculty in 1987.

Professor Meyer's research focuses on the application of sensitive spectroscopic techniques to astrophysical problems involving interstellar and extragalactic gas clouds. Using a variety of ground- and space-based telescopes, he studies the optical and ultraviolet spectra of stars and quasars to better understand the composition, structure, and physical conditions of intervening clouds in the Milky Way and other galaxies. Over the course of the past 15 years, much of his research has involved data from the Hubble Space Telescope (HST). During this time, Professor Meyer and his collaborators have been awarded more than $1 million in research funding to carry out 20 HST projects that have resulted in 25 peer-reviewed publications on topics ranging from the abundance of interstellar oxygen to the gaseous character of distant galaxies. He has also served 5 times on the committee that annually selects the most deserving proposals for HST observing time.

During his career at Northwestern, Professor Meyer has specialized in designing and teaching introductory undergraduate courses in astronomy, cosmology, and astrobiology for nonscience majors. A hallmark of his

lectures is the use of HST images to bring the latest research into the introductory classroom. His success in such efforts has led to a number of teaching awards. In 2009, Professor Meyer was awarded Northwestern's highest teaching honor, the Charles Deering McCormick Professorship of Teaching Excellence. His previous honors include the Koldyke Outstanding Teaching Professorship (2002), the Weinberg Distinguished Teaching Award (1999), and the Northwestern University Alumni Excellence in Teaching Award (1998). He has also reached out to students young and old beyond the Northwestern campus by delivering popular talks on HST science to alumni groups in settings as unusual as a transatlantic crossing of the *Queen Mary 2* in 2005. ■

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INTRODUCTION

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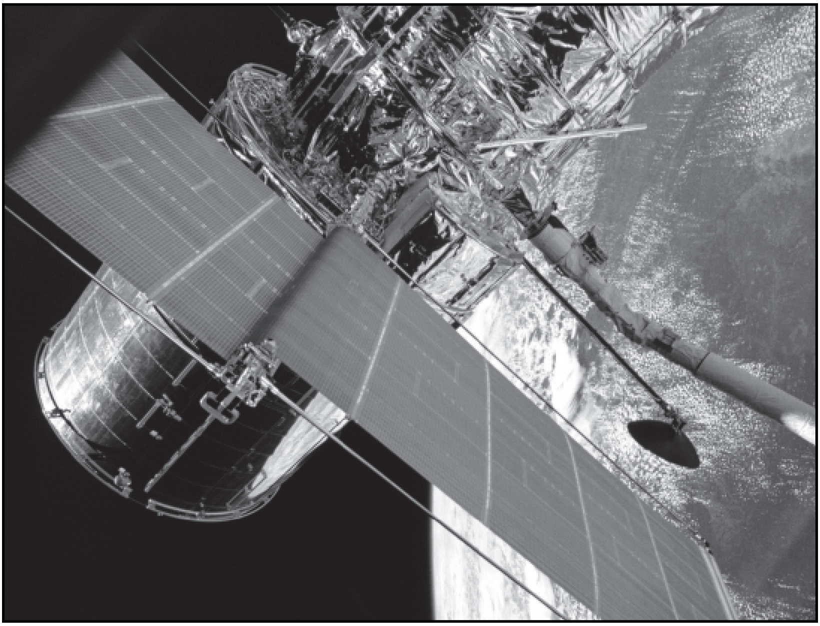
Experiencing Hubble: Understanding the Greatest Images of the Universe

Scope:

The Hubble Space Telescope (HST) has revolutionized our understanding of the universe both near and far. Its stunning images of stars, nebulae, and galaxies have captivated public attention and inspired students of all ages. The sharpness of HST's images owes to the telescope's location in near-Earth orbit, well above the blurring effects of atmospheric turbulence. Indeed, HST can routinely image the universe with a resolving power more than 10 times better than that of the largest ground-based telescopes. Since its launch in 1990, HST has taken more than a half million cosmic images and astronomers have published more than 7,000 scientific papers based on HST data. These papers have reported groundbreaking discoveries on a variety of topics, ranging from the formation of stars, to the collisions of galaxies, to the accelerating expansion of the universe.

In this introductory course, we discuss the scientific stories behind 10 of HST's most spectacular images. These 10 images were chosen on the basis of their visual beauty and scientific impact and to illustrate the breadth of HST astronomy. The lectures are organized to address the images one by one from near to far, beginning with the solar system, then on to stars and nebulae in the Milky Way Galaxy, individual galaxies, systems of galaxies, and finally, the universe at large. In each of these lectures, the HST image is discussed in terms of its broad astrophysical context and the specific implications of its findings. Along the way, these "Hubble stories" provide an inside look at the history and operation of HST as it is used to attack the most important problems in modern astrophysics. A key emphasis throughout the course is how HST's unique imaging capabilities have made its discoveries possible. Specific contrasts are drawn between HST's view of the universe and those of the naked eye and ground-based telescopes.

The course begins with an introductory lecture on light and telescopes. It focuses on the advantages of HST over ground-based telescopes and the



Since its launch, the Hubble has taken over a half million images of planets, stars, nebulae, and galaxies, and astronomers have published over 8,000 scientific papers based on Hubble data.

1993 space shuttle servicing mission that installed corrective optics to overcome the spherical aberration of HST's 2.4-meter-diameter primary mirror. We then voyage to the planet Jupiter, whose deep atmosphere was buffeted by the impact of multiple kilometer-sized fragments of Comet Shoemaker-Levy 9 in 1994. The HST image of the temporary Earth-sized scars left by these impacts on Jupiter serves as a contemporary reminder of the continuing impact threat to Earth posed by comets and asteroids. Our first stop outside the solar system is the Sagittarius Star Cloud—one of the richest star fields in the Milky Way. HST's view of the inner star cloud region reveals a sparkling jewel box of colors that is particularly appropriate for a discussion of the wide variety of stars that populate the galaxy. We travel next to the Eagle Nebula to study an active site of star formation inside a vast interstellar cloud of gas and dust. The now-famous HST image of newborn stars emerging from their dusty cocoons at the heart of this nebula was the first to reveal star birth in such detail. Our visit to the Cat's Eye

Nebula provides an opportunity to witness and discuss the final stages in the death of a solar-type star. The multiple gas shells evident in the penetrating HST view of this planetary nebula are the blown-off outer layers of the dying central star. We then explore the violent deaths of the most massive stars through the HST mosaic of the Crab Nebula—the gaseous remnant of a supernova explosion observed on Earth in the year 1054. Such explosions are the primary galactic source of atomic elements, such as oxygen and iron, that make planetary life possible.

The most spectacular HST image of an individual galaxy is that of the magnificent Sombrero Galaxy—a nearly edge-on spiral at a distance of 29 million light-years. Through this image, we discuss the character of galaxies in the local cosmos and the history of their discovery as "island universes" far beyond the Milky Way. We then turn to the deep HST view of the distant galaxies in the sky field of the foreground spiral NGC 3370 to introduce the evidence for an expanding universe. HST observations of Cepheid variable stars and supernovae in NGC 3370 and other galaxies have recently shown that this expansion is accelerating under the mysterious influence of dark energy. Although the overall universe is expanding, the colorful HST image of the colliding Antennae Galaxies shows that gravity can overcome this expansion in regions where galaxies are clustered. We explore this image in the context of what to expect when the nearby Andromeda Galaxy begins to collide with the Milky Way about 2 billion years from now. Some clusters of galaxies are so massive that they curve the surrounding space to an extent that the images of background galaxies are distorted as their light passes through this space. As the most dramatic example of such a gravitational lens, we investigate the HST observations of the cluster Abell 2218 and its implications regarding the dominance of dark matter in the universe. The last of our top-10 HST images is the Hubble Ultra Deep Field—the deepest optical survey of the universe made to date. We discuss how the evolution of galaxies evident in this image is consistent with the idea that the universe began with a Big Bang 13.7 billion years ago. The course concludes with a lecture on the future of HST and the space telescopes to follow in its footsteps, specifically, the James Webb Space Telescope. The lecture focuses on the capabilities of these telescopes in opening up one of the key research frontiers in modern astrophysics—the detection and characterization of extrasolar planetary systems. ■

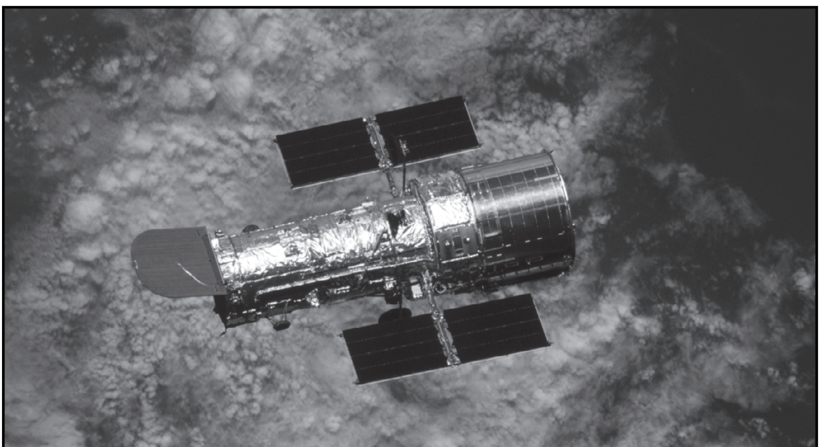
The Rationale for a Space Telescope

Lecture 1

One might view this course, actually, as the science equivalent of an art appreciation course. We're going to discuss Hubble's images in the context of the telescope's capabilities and the underlying astrophysics in a similar way that one might discuss an artist's masterpieces in the context of the artist's style and the times during which they were painted.

In this first lecture, we discuss the key advantages of a space telescope over a ground-based observatory in imaging the cosmos. Understanding these advantages requires a brief introduction to the basics of light, telescopes, and the Earth's atmosphere. We will then discuss the attributes of Hubble as designed and how its early performance in Earth orbit nearly shattered its promise as a revolutionary space telescope.

Almost everything we know about the universe beyond the solar system comes from observations of **electromagnetic radiation**. The optical light we see with our eyes is one form of electromagnetic radiation. Light is made of wavelike particles called **photons**, which exhibit an inverse relationship

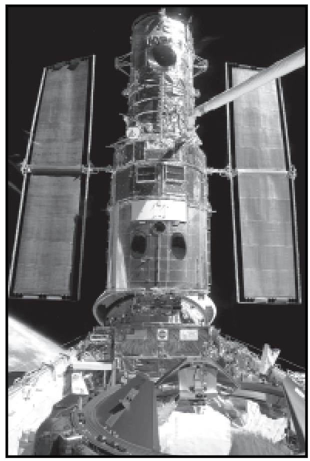


NASA.

Every 97 minutes, Hubble travels around the Earth in a low-Earth orbit.

between their wavelength and energy: Higher-energy photons have shorter wavelengths, and lower-energy photons have longer wavelengths. The shortest-wavelength photons are gamma rays, and from there, the spectrum proceeds to X-rays, ultraviolet light, optical light, infrared light, microwaves, and radio waves.

Each region in the electromagnetic spectrum gives us a different view of the cosmos, and it does this because there's a wide range of processes in the universe that emit radiation at different wavelengths. Our atmosphere is transparent only at optical, radio, and select wavelengths in the infrared and microwave regions of the spectrum. One of the key advantages of a space telescope is that it can observe astronomical objects and processes that emit photons at wavelengths that can't be seen from the Earth's surface.



NASA/STScI.

Hubble was designed with a complement of instruments to image and take spectra of astronomical objects.

Most of the telescopes used in astronomical research today are reflectors, which use a curved mirror to focus starlight. The design of a reflecting telescope must ensure that the focus is not in the way of the light path. The **Cassegrain** design, that's used in the Hubble and other telescopes, accomplishes this as follows: A large primary mirror collects starlight, then bounces the starlight off a smaller secondary mirror, which then sends the light through a small hole in the primary mirror to the focus behind the telescope.

Astronomers are always looking to build telescopes with larger mirrors because a larger mirror collects more light and can resolve smaller angular separations in the sky. From one horizon to another in the sky is 180 degrees. If we used a protractor to measure the angle that the Moon subtends on the sky, we'd come up with 1/2 degree, but astronomers use smaller units of angle: arc minutes (60 arc minutes in 1 degree) and arc seconds (60 arc seconds in 1 arc minute). Using this system, the 1/2-degree Moon is 1,800 arc seconds.

If we're looking at two stars separated by an angle of 1 arc second using a telescope with a diameter of 1/10 of a meter, the telescope can just barely resolve those two stars. Our atmosphere, however, poses a problem for increasing resolution with bigger telescopes: The atmosphere is always in motion, and it distorts starlight, causing the effect of twinkling. We might have a huge telescope on the ground, but we're unable to get a sharp image because of this twinkling starlight.

There are two basic approaches to improving **resolving power**. One is to work with mountaintop telescopes using a technology called "adaptive optics"; this technology has had some successes, but there are limits to what it can do, especially beyond tiny fields of view in the sky. The other option is to put the telescope above the atmosphere. The primary rationale for Hubble was the scientific desire for a large telescope in Earth orbit that would be capable of routinely imaging the cosmos with a resolving power more than 10 times better than that of the largest ground-based optical telescopes.

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Hubble was put in low-Earth orbit (600 kilometers altitude) for several key reasons, one of which was to enable it to be launched and serviced with the space shuttle. This servicing capability proved to be vital when, shortly after launch in 1990, it was discovered that Hubble's resolving power wasn't much better than that of ground-based telescopes. It turned out that the primary mirror was flawed. But there was also another fix needed for an even higher-priority problem. Since launch, astronomers had noted that whenever Hubble crossed the terminator—the point of change from day into night and night into day—the solar panels would flap because they were not rigid enough for night/day heat stress associated with this terminator crossing. The flapping solar panels could break off, causing Hubble to lose power. If Hubble lost power, it couldn't keep the instruments hot enough to function, and the mission would be over.

The 1993 servicing mission made it possible for Hubble to achieve its design goal of imaging the optical universe at an unprecedented sky resolution. It was also a shining success for NASA in demonstrating that astronauts could perform difficult, detailed work in the space environment. ■

Important Terms

Cassegrain telescope: A telescope in which incoming starlight is reflected off a primary mirror to a secondary mirror that then reflects it back through a small central hole in the primary mirror to an eyepiece or instrument behind the primary.

electromagnetic radiation: Commonly referred to as "light" at optical wavelengths, this radiation is due to oscillating electric and magnetic fields.

photon: The particle that carries electromagnetic radiation (light) with wavelike characteristics.

resolving power: A measure of the smallest angular separation that a telescope can resolve in an image.

Suggested Reading

McCray, *Giant Telescopes*.

Smith, *The Space Telescope*.

Zimmerman, *The Universe in a Mirror*.

Questions to Consider

1. What would be the advantages and disadvantages of observing the universe with a large telescope on the Moon's surface as compared to one in low-Earth orbit?

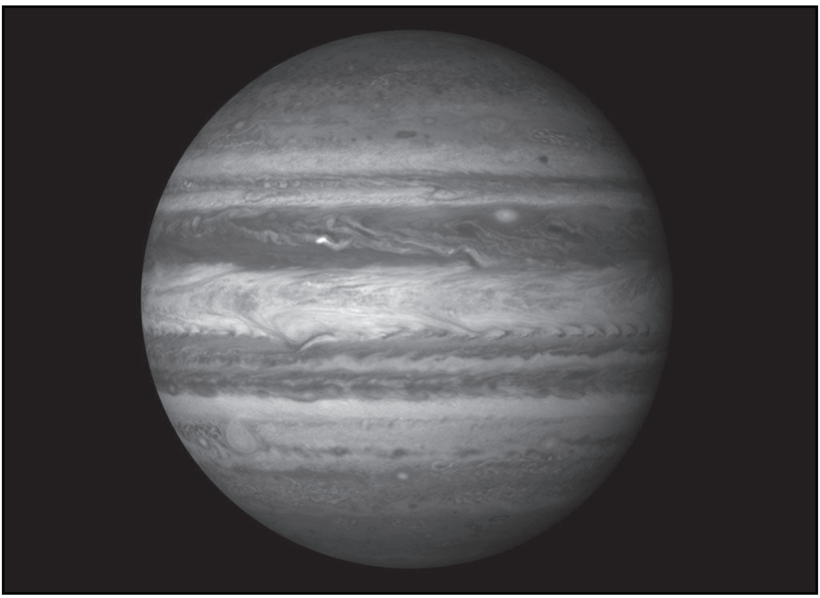
2. Given the success of the HST, why do astronomers continue to build bigger and bigger Earth-based telescopes?

Comet Shoemaker-Levy 9 and Jupiter

Lecture 2

The importance of Shoemaker-Levy 9 is it kind of woke up the astronomical community. It said, "Hey, this is a problem. We just saw Jupiter get whacked; we see that these things have hit the Earth in the past. The rate at which a kilometer-sized asteroid hits the Earth is not zillions of years; it's a couple hundred thousand years. This is something we should get concerned about."

Shortly after the 1993 servicing mission brought Hubble back to where it should have been, astronomers were given an amazing opportunity to witness the solar system event of the century. Over the course of one week in July 1994, 20 fragments of Comet Shoemaker-Levy 9 slammed into



NASA.

In July 1994, 20 fragments of Comet Shoemaker-Levy 9 slammed into the planet Jupiter. Hubble took a detailed image of Jupiter that revealed a series of Earth-sized impact scars across its cloudtops.

the planet Jupiter. As the cometary barrage ended, Hubble took a detailed image of Jupiter that revealed a series of Earth-sized impact scars across its cloudtops, showing us that such an impact could actually happen during our lifetime.

The drama we will discuss today began in March 1993 when Eugene and Carolyn Shoemaker and David Levy discovered their ninth **comet**, which had a "squashed" shape. Immediately after this unusual comet became known to the astronomical community, follow-up ground-based and Hubble observations of the comet were made. These showed at higher resolution that the comet consisted of multiple fragments, and over time, these fragments were slowly increasing in separation. Even Hubble's initial observations of Shoemaker-Levy 9 in 1993, before its vision was corrected, could easily resolve these fragments.

It became apparent that this comet was orbiting Jupiter (which is extremely unusual); that in July 1992, it had actually passed close enough to Jupiter to be broken into pieces by the planet's gravity; and that it would smash into Jupiter in July 1994. With more than a year to plan for this impact, astronomers could marshal the Hubble and other kinds of observatories to witness this particular event. Two months before the impact, Hubble had a new chance to look at Shoemaker-Levy 9 after its vision had been completely restored as a result of the 1993 servicing mission. It produced an amazing image of Shoemaker-Levy 9 showing 21 individual fragments stretching across 700,000 miles of space, and each one of these fragments had its own little tail.

Most Hubble observations require weeks or more of processing and analysis before the "eureka" of discovery can occur, but with the first Shoemaker-Levy 9 impact, a naked-eye glimpse of the raw images told the tale.

Most Hubble observations require weeks or more of processing and analysis before the "eureka" of discovery can occur, but with the first Shoemaker-Levy 9 impact, a naked-eye glimpse of the raw images told the tale. The first fragment of Shoemaker-Levy 9 smashed into Jupiter's night side at a

speed of more than 60 times faster than that of a rifle bullet. Even ground-based telescopes showed a fireball rising from behind the planet edge. These observations were consistent with the prediction that these fragments were roughly about a kilometer in size and they would hold together long enough to get below the clouds, explode, then vent the hot gas as a fireball. As the first impact site rotated into sunlight view 90 minutes later, Hubble revealed an impressive, Earth-sized, dark scar on the Jovian cloudtops. Overall, 20 impacts were recorded, with energies ranging from the equivalent of 1 million to 100 million Hiroshima atomic bombs.

At the time of this comet's impact, the astronomical community was uncertain about the number and sizes of **Near-Earth Objects**. A Near-Earth Object is an object that has an orbit that intersects the Earth's orbit; these are the objects that are most likely to hit the Earth. Shoemaker-Levy 9 served as a wake-up call to astronomers. Since its impact, a number of surveys have discovered 6,300 Near-Earth Objects, 800 of which are kilometer-sized or larger. It's believed that this represents about 80 percent of the total number of such large objects. The good news is that these surveys can plot these objects' orbits, and none of the ones identified so far poses a significant immediate threat.

The Shoemaker-Levy 9 impact in 1994 showed us that violent cosmic events could, at least temporarily, dramatically change the face of familiar objects in the solar system during our lifetime. It also demonstrated that Hubble has the power to monitor such events in real time with unparalleled accuracy. ■

Important Terms

comet: A kilometer-sized object of ice and rock that produces a visible tail of vapor and dust as it approaches the Sun during the course of its orbit.

Near-Earth Object (NEO): A nearby asteroid whose orbit intersects that of Earth.

Suggested Reading

Crovisier and Encrenaz, *Comet Science*.

Levy, *Impact Jupiter*.

Questions to Consider

1. Imagine that the fragments of Comet Shoemaker-Levy 9 had hit Mars instead of Jupiter. What would the impacts and aftermath have looked like as observed with the HST?

2. Imagine that a kilometer-sized asteroid is discovered on an orbital trajectory to impact the Earth in 200 years. What, if anything, could (or should) be done in the next 50 years to try to prevent this catastrophe?

The Sagittarius Star Cloud

Lecture 3

The total sky area encompassed by this image [of the Sagittarius Star Cloud] is half a percent of the full Moon sky area; just a tiny fraction of the Moon's sky area is in this image, effectively—12,000 stars. That's four times more stars than if you went outside at night and counted all the stars you could see with your eyes.

In this lecture, we leave the solar system and begin to explore the Milky Way Galaxy with Hubble. Our first stop is the Sagittarius Star Cloud, one of the richest star fields in the night sky and located near the center, or bulge, of our galaxy. The Hubble view of the star cloud looks like a sparkling jewel box in the sky and illustrates one of the major advantages of Hubble over ground-based telescopes: its ability to image the cosmos at very high spatial resolution and to distinguish closely spaced stars. With a ground-based telescope, the light from many of the stars in this dense star cloud will blend together. That's a problem if we want to try to compare the properties of nearby stars to more distant stars. The Hubble is able to clearly show stars in the Sagittarius Star Cloud in a wide variety of colors and brightnesses.

The brightness of a star is a function not only of how bright it truly is (its luminosity) but also its distance. If we know the luminosity and brightness of a star, we can calculate its distance. We can estimate a star's intrinsic luminosity by using the **Hertzsprung-Russell (HR) diagram**, which describes stars in terms of their surface temperatures and luminosities. Using the HR diagram, we can easily measure the color of a star, then infer its temperature and luminosity. Combining that information with a measure of the star's brightness, we can get the distance of the star.

By resolving out the colors and brightnesses of individual stars in the Sagittarius Star Cloud and other dense star fields, Hubble facilitates the application of the HR diagram to determine the distances of stars and estimate their ages. Older stars are red and cooler; younger stars are blue and hotter. The Hubble image reveals that the distant stars in the galactic bulge

have a redder color distribution than those stars near the Sun, indicating that the stellar population near the bulge consists of older stars than those in the solar neighborhood.

The ages of stellar populations in the galactic halo can also be probed through studies of its **globular star clusters**. There are 150 of these globulars scattered throughout the galactic halo—that is, outside the spiral and center of the galaxy. The dense star fields of these globulars are an attractive target for the Hubble. The results can be surprising: The HR diagram for the cluster M80, for example, reveals that this cluster is more than 10 billion years old, yet Hubble's superior resolution has discovered blue stars at the core of this old globular, a surprise that has astronomers proposing that old stars collide and combine to make hotter ones.

The HR diagram for the cluster M80, for example, reveals that this cluster is more than 10 billion years old, yet Hubble's superior resolution has discovered blue stars at the core of this old globular, a surprise that has astronomers proposing that old stars collide and combine to make hotter ones.

By resolving out the colors and brightnesses of individual stars in dense fields, like the Sagittarius Star Cloud and globular clusters, Hubble is helping to chart the stellar history and evolution of the Milky Way. Clearly, this evolution is keyed by the nature, timing, and extent of star formation in various regions of the galaxy. ■

Important Terms

globular star cluster: A densely packed, spherical cluster of up to a million old stars typically found in the halos of galaxies.

Hertzsprung-Russell (HR) diagram: A diagram comparing the temperatures and luminosities of stars that is useful in charting their evolution over time.

Suggested Reading

Kaler, *Extreme Stars*.

———, *The Hundred Greatest Stars*.

Sparke and Gallagher, *Galaxies in the Universe*.

Questions to Consider

1. How would the night sky look to the naked eye on Earth if there were no dust clouds in the Milky Way Galaxy? How would the night sky look if the Earth was located at the center of a globular cluster?

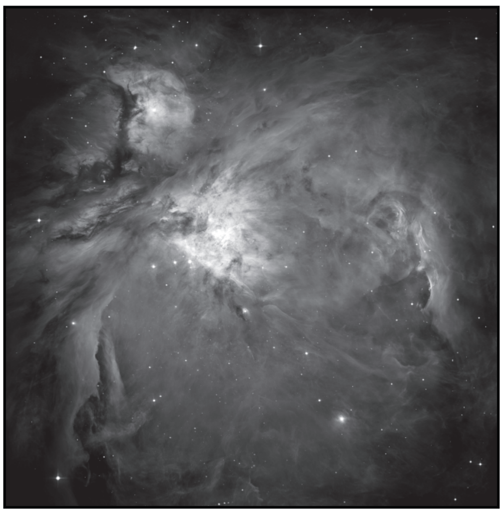
2. How would the HST view of a dustier region of the Milky Way disk contrast with that of the Sagittarius Star Cloud? How would the HR diagrams of these two regions compare?

The Star Factory Inside the Eagle Nebula

Lecture 4

How were [the Eagle Nebula] pillars sculpted? Nearby hot stars, as their radiation and stellar winds were working on the inside of this molecular cloud, evaporated the less dense material around the pillars, slowly eating it away and uncovering the denser parts, uncovering these dense stalks, uncovering these globules, and beginning to reveal … that there were stars forming inside.

Some of the most breathtaking Hubble images have involved its observations of interstellar clouds at unprecedented resolution. Among these Hubble cloud images, none has been received with greater public acclaim than the detailed 1995 snapshot of newborn stars emerging from giant pillars of gas and dust inside the Eagle Nebula.



NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA), and the Hubble Space Telescope Orion Treasury Project Team.

The Orion Nebula can be seen as a faint whitish glow with the naked eye. The illumination of the Orion Nebula comes almost entirely from four really hot stars called the Trapezium Stars deep inside the nebula.

Any wide-field view of the Milky Way across a dark sky reveals the existence of obscuring dust clouds in the disk of the galaxy. These clouds of dust and gas contain in total about 15 percent of the galaxy's visible mass, with the gas making up the bulk of this fraction. The grains of stardust absorb and scatter background starlight; for this reason, dense clouds of gas are also typically dark clouds. In these individual clouds, even though the densities are low, atoms can run into each other and form

molecules. Astronomers typically refer to dark clouds as molecular clouds because they have great numbers of molecules deep in their cores. We find molecules ranging from formaldehyde to ethyl alcohol; indeed, some molecules have as many as 13 atoms in them.

These dense regions of dark molecular clouds are important because they contract under their own gravity, their interiors slowly heat up until core hydrogen fusion begins, and a star is born. Active star formation is taking place in the Orion Nebula, the most visible of these gas/dust clouds, but most of this formation is obscured by the very dusty cloud. We depend on infrared and radio telescopes to tell us what's going on in there.

Active star formation is taking place in the Orion Nebula, the most visible of these gas/dust clouds, but most of this formation is obscured by the very dusty cloud. We depend on infrared and radio telescopes to tell us what's going on in there.

Fortunately, the Eagle Nebula provides an optical view inside a large molecular cloud that has produced thousands of stars. The wide-field nebular glow of the Eagle Nebula covers a sky area greater than the full Moon. This glow is excited by the ultraviolet light from an interior cluster of 50 hot young stars that were born inside the cloud. The winds and the radiation from these stars have shaped this cloud over millions of years; they've helped to open a 20-**light-year**–wide window into the cloud so that we can see its sculpted interior with Hubble and other ground-based telescopes at optimal wavelengths.

In 1995, Hubble took our close-up image of the prominent gas/dust pillars at the core of the Eagle Nebula and revealed the wealth of illuminating small-scale structure. The image reveals details on the tallest pillar—thin protuberances—some of which appear to have stars emerging from the globules at the tips. To give a sense of scale, the globules here are 400 times the Earth-Sun distance, and the tallest pillar is 4 light-years in length. The globules are essentially cocoons of gas and dust for the formation of stars.

Stars form as a result of the contraction of dense cloud regions. As a cloud rotates, it contracts (the principle of conservation of angular momentum), and as it gets smaller, it also forms an accretion disk around the developing inner star. The disk funnels matter into the central protostar. Sometimes this matter can come in too fast for the protostar to swallow; in this case, the matter is channeled out into bipolar outflows from the forming star. The disk that's left over from star formation may eventually lead to the formation of planets. The bottom line is: Star formation leads not only to stars but also to jets, disks, and perhaps, planet growth. ■

Important Term

light-year: The distance (6 trillion miles) that light travels in one year.

Suggested Reading

Kaler, *Cosmic Clouds*.

O'Dell, *The Orion Nebula*.

Questions to Consider

1. How might the wide-field and HST views of the Eagle Nebula lead us to conclude that the star formation process in a large molecular cloud is rather inefficient in converting interstellar gas and dust into stars?

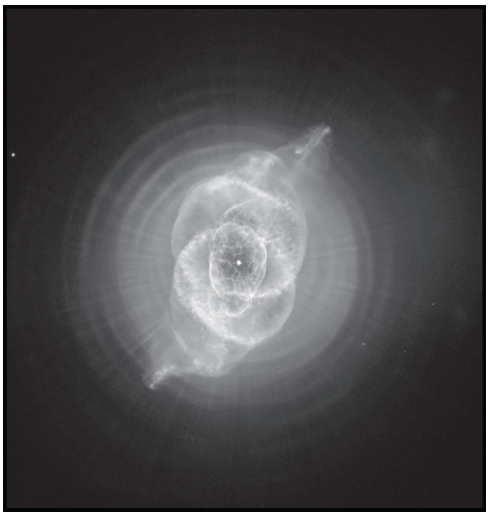
2. Why has the HST image of the Eagle Nebula become so popular?

The Cat's Eye Nebula—A Stellar Demise

Lecture 5

The total mass in this outer halo is about half that of the Sun. What it is, is basically the outer-envelope ejecta of the red giant that eventually produced both this and the inner Cat's Eye, and this outer envelope was ejected on the order of 25,000 years ago, based on the speed that we see this outer halo expanding.

The gaseous nebulae that are associated with the births of stars are also associated with the deaths of stars; the expanding ash cloud that attends the death of a solar-type star is a colorful sky object called a **planetary nebula**. The detailed Hubble views of planetary nebulae allow astronomers to look into the exposed innards of dying stars and essentially perform a stellar autopsy. It's the ultraviolet radiation from the dying star that ionizes the atoms in these expanding gas shells that the star has thrown out, and as a result, the gas shells glow. About 3,000 planetary nebulae have been identified.



NASA, ESA, HEIC, and The Hubble Heritage Team (STScI/AURA). Acknowledgments: R. Corradi (Isaac Newton Group of Telescopes, Spain) and Z. Tsvetanov (NASA).

When we look at the Cat's Eye Nebula, we don't see it as it is now; we see it as it was 3,000 years ago. Its structure of rings, bubbles, and knots is complex in detail but beguilingly symmetric in overall appearance.

Among these planetaries, the Cat's Eye Nebula clearly stands out as a top-10 Hubble image. Its structure of rings, bubbles, and knots is complex in detail but beguilingly symmetric in overall appearance. It was discovered in 1786 by the British astronomer Sir William Herschel, who catalogued many galactic nebulae and discovered the

NASA, ESA, and The Hubble Heritage Team (STScI/AURA).

The bipolar bubbles and flows, as seen in the Ant Nebula, could possibly be shaped by a strong stellar magnetic field or perhaps by a gravity field of a close companion star.

planet Uranus. Indeed, Herschel came up with the term “planetary nebula” for objects like the Cat’s Eye because their sky appearance resembled the small green disk of Uranus.

As we study the Hubble image of the Cat’s Eye, we notice several features. We see a series of outer concentric rings of light. These seem to be the result of symmetric mass ejections from the star every 1,500 years for the past 15,000 years. As we get closer to the central star, we see that the Cat’s Eye has an axis to it, a bipolar symmetry. As with many Hubble images, this one results in many more questions than it does answers.

The most detailed Hubble image of a planetary nebula in terms of physical length/scale is that of the nearby Helix Nebula. If we look at the Helix with Hubble, we see thousands of cometary knots of gas and dust in the ejecta; each one of these knots is about the size of the solar system. Likewise, if we look at the Eskimo Nebula, we see an inner bubble structure that looks somewhat similar to the Cat’s Eye Nebula, and the Spirograph Nebula also has this filamentary bubble-like structure similar to the Eskimo and the Cat’s Eye nebulae.

The Butterfly Nebula has a dusty central torus and fan-shaped outflows of material coming from the central star. Studies of this object show that the central star was probably originally about 5 times the Sun's mass.

It’s clear that planetary nebulae exhibit remarkable symmetry and a shape that’s circular, elliptical, or bipolar. It’s also clear that planetaries exhibit a wide variety in their small-scale structures, whether these are rings, knots, or bipolar structures. Some of the most fascinating planetaries that Hubble has looked at, even though they are very rare, are the bipolar planetaries, such as the Ant Nebula. The Ant Nebula reveals bipolar bubbles and flows; these might be shaped by a strong stellar magnetic field or the gravity field of a close companion star. Another spectacular bipolar planetary observed with the HST is the Butterfly Nebula, also known as the Bug Nebula. When we look at this object, we see that it has a dusty central torus and fan-shaped outflows of material coming from the central star. Studies of this object show that the central star was probably originally about five times the Sun’s mass.

The mass of a typical white dwarf is about half that of the Sun, and its size is about that of the Earth.

After the mass loss ends and the planetary nebula moves away, the exposed core left behind at the center of a typical planetary settles down into a **white dwarf**. The central object in the Ring Nebula, for example, is a white dwarf. That’s the exposed core of the former **red giant**. The mass of a typical white dwarf is about half that of the Sun, and its size is about that of the Earth. Something that is half a solar mass condensed into something the size of the Earth is obviously going to be very dense, and indeed, a white dwarf is much denser than lead. Although white dwarfs are initially very hot—their temperatures can be more than 20 times the surface temperature of the Sun—they are quite faint because of their small size; remember, they’re about the size of the Earth. The brightest star in the sky, Sirius, is only 8.6 light-years away, but its white dwarf companion (the first white dwarf discovered) is far too faint to be seen with the naked eye; indeed, it’s 10,000 times fainter than Sirius.

A white dwarf does not generate nuclear fusion energy. It’s like a dying coal in a fireplace, and it slowly radiates its heat away. As time goes on, it will change from being a white dwarf to a red dwarf and, in billions of years, become a black dwarf, a dead hunk of matter the size of the Earth but half the mass of the Sun and as black as space. ■

Important Terms

planetary nebula: The short-lived nebula (lasting for about 50,000 years) that results when a dying red giant blows off the gaseous layers surrounding its core.

red giant: After a solar-type main-sequence star fuses all of its core hydrogen into helium, it evolves into this type of cooler, larger, more luminous star.

white dwarf: The final stage in the evolution of the Sun (and 99 percent of the stars in the Milky Way Galaxy); a compact, Earth-sized object radiating its remnant energy like a dying coal in a fireplace.

Suggested Reading

Balick, "How the Sun will Die."

Balick and Frank, "Shapes and Shaping of Planetary Nebulae."

Kwok, *Cosmic Butterflies*.

Questions to Consider

1. Why are planetary nebulae typically much more symmetric than the nebulae associated with star-forming regions?

2. Is it likely that there are elemental composition differences between the outermost and innermost gas shells in the Cat's Eye Nebula? Why?

The Crab Nebula—A Supernova's Aftermath
Lecture 6

[Betelgeuse is] going to go supernova. It's a red supergiant; it will explode as a Type II supernova, but when? It will happen sometime in the next 100,000 years; we can be certain of that. It could happen within the next 10,000 years. It could happen tonight. Predicting when a given star is going to blow up as a supernova is much harder than even predicting earthquakes, which is very hard to do.

The relatively few stars born with a mass exceeding 8 solar masses are the hottest and the most luminous stars on the main sequence, and they quickly evolve to a spectacular termination within just a few million years. They detonate in a colossal explosion known as a supernova, with a peak luminosity equivalent to a billion Suns. Among **supernova remnants**, none is more famous than the Crab Nebula. Its position in the sky corresponds to the location of a supernova witnessed on Earth in the year 1054. The Hubble image of the Crab certainly looks like the aftermath of a violent explosion; it lacks the graceful symmetry of a planetary nebula. We will explore this Hubble image in the context of its present physical character and the supernova explosion that produced it.

Among supernova remnants, none is more famous than the Crab Nebula. Its position in the sky corresponds to the location of a supernova witnessed on Earth in the year 1054.

Observations and theoretical models show that once a massive star leaves the main sequence, it evolves quite differently than does a star like the Sun. Specifically, as the core of such a star contracts to a temperature and density at which helium fusion can begin, the star expands into a red **supergiant** with a diameter greater than that of the current orbit of Mars around the Sun. After the helium in the massive core runs out, the core continues to contract under gravity, forcing carbon fusion into a heavier element, such as neon, which then fuses into a heavier element and so on to iron, with each succeeding stage of fusion going faster.

NASA, ESA, J. Hester, and A. Loll (Arizona State University).

Stars born with a mass exceeding eight solar masses are the hottest and the most luminous stars; they quickly evolve to a spectacular termination within just a few million years. These stars detonate in a colossal explosion known as a supernova with a peak luminosity equivalent to a billion Suns. Among these supernova remnants, none is more famous than the Crab Nebula.

This star is poised for destruction; indeed, the gravitational collapse of the iron core leads to the destruction of the supergiant in a supernova explosion. Iron does not produce energy through fusion; gravity in the core is essentially unopposed. The collapse is so violent that it smashes the core electrons into the protons, converting the core into almost pure neutron matter and releasing a flood of energy in particles called **neutrinos**. When the resultant neutrino shockwave reaches the star surface, we see a supernova explosion. We call these explosions core-collapse supernovae. They are among the

brightest objects we can see in the sky; at maximum brightness, a core-collapse supernova can achieve a luminosity of 1 billion Suns.

The records of naked-eye supernovae date back 2,000 years. Chinese, Japanese, Arabic, and even Native American astronomers noted one that occurred in July 1054. Today, when astronomers point their telescopes at the location where this supernova occurred, they see a filamentary web of gas that is 12 light-years across and expanding at a velocity more than 1,500 times faster than a rifle bullet. This Crab Nebula provides evidence for a very turbulent medium; the Hubble image shows large filaments breaking up into tinier filaments. The inner blue glow is powered by a rapidly rotating **neutron star** called a **pulsar** at its center; it's the collapsed core remnant of the exploded supergiant, an object of pure neutron matter.

The neutron star at the very heart of the Crab supernova remnant pulses at a rate of about 30 times a second, and not just in radio light but also in optical light. The speed of this pulsar spin is the result of the increasing rate of rotation at the core as it contracted. The magnetic axis of this pulsar is not the same as its rotation axis; thus, as the pulsar rotates, the powerful magnetic axis swings around rapidly, beaming high-speed electrons like a searchlight and lighting up the nebula with a blue glow.

Hubble has also imaged other supernova remnants, none more frequently than the site of the 1987 supernova in the Large Magellanic Cloud. Observations clearly show a supernova remnant in formation. In the 1990s, the supernova's shockwave began hitting an inner gas ring cast off thousands of years ago by the pre-supernova supergiant. Shock-heated gas glows at the impact points where the shock hit this inner ring, and the ring is now lit up like a pearl necklace from these impact points. The supernova remnant itself is already a light-year in size since it exploded in 1987.

We are quite fortunate that there is no star anywhere near Earth that is likely to go supernova in at least the next 10,000 years. However, we are overdue for the kind of sky show that our ancestors wondered about when the distant Crab supernova exploded in 1054. Indeed, it's quite likely that one of the distant massive stars observable in the sky tonight has already exploded, and it's only a matter of time before we see this event. ■

Important Terms

neutrino: An elementary particle of very low mass produced in nuclear reactions, such as those in the solar core and Type II supernovae.

neutron star: The collapsed core remnant of a Type II supernova; it typically has a mass of about 1.5 solar masses within its radius of 10 kilometers.

pulsar: A rapidly rotating neutron star.

supergiant: After a massive main-sequence star fuses all of its core hydrogen into helium, it eventually evolves into this type of very large, very luminous, cool star.

supernova remnant: The expanding, nucleosynthetically enriched gaseous remnant of a star that has undergone a supernova explosion.

Suggested Reading

Hester, "The Crab Nebula: An Astrophysical Chimera."

Wheeler, *Cosmic Catastrophes*.

Questions to Consider

1. How could HST observations alone lead us to conclude that the Crab Nebula is a supernova remnant rather than an odd planetary nebula?

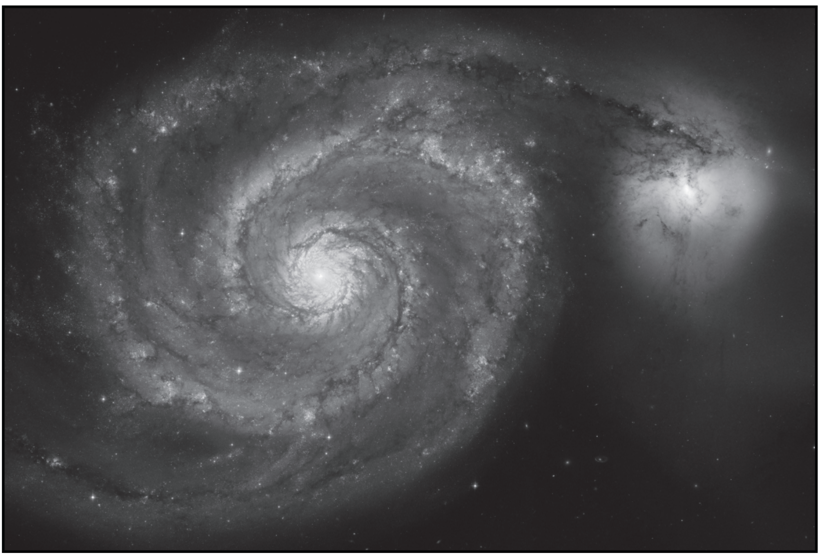
2. Why is HST much less likely to discover the next galactic supernova than a ground-based observer?

The Sombrero Galaxy—An Island Universe

Lecture 7

The galaxies nearest our Milky Way form a cluster called the Local Group. The Local Group consists of 40 or so galaxies. It's dominated by three big spirals: the Milky Way; Andromeda; and M33, the Triangulum Galaxy. The rest of the galaxies in the Local Group are dwarf ellipticals, irregulars, and dwarf spheroidals.

In this lecture, we discuss Hubble images of galaxies in the context of the discovery, characteristics, and local distribution of these "island universes," a term originally coined by the German philosopher Immanuel Kant in 1755. Galaxies were known to astronomers long before their recognition as individual star systems far from the Milky Way. In the 1770s, the French astronomer Charles Messier catalogued more than 100



NASA, ESA, S. Beckwith (STScI), and The Hubble Heritage Team STScI/AURA).

Spiral galaxies are gas-rich systems of young and old stars. The Whirlpool Galaxy (M51) is a classic face-on Sc spiral. It has a kind of small bulge with large, loosely wound arms. An Sa spiral would have a bigger bulge and more tightly wound arms.

fuzzy objects in the sky that were fixed with respect to the stars. The Crab supernova remnant (known as M1) was the first object on Messier's list. Using Messier's catalogue, scientists noted that fuzzy objects above and below the plane of the Milky Way showed much more symmetry than ones in the plane, with some being spherical and others globular. Another class of fuzzy objects exhibited a spiral symmetry, and these spiral nebulae were a complete mystery. How far away they were continued to be a mystery until the early 1920s.

A key part of the solution to the spiral nebulae problem came from the work of Henrietta Leavitt in the early 1900s. Leavitt noticed that there is a relationship between the period of a **Cepheid variable** star and its luminosity; specifically, she found that the Cepheids that have longer periods are more luminous. This Cepheid period-luminosity relationship enables astronomers to derive the distance to any star group that has a Cepheid in it. The man who used the Cepheid period-luminosity relation to solve the spiral nebulae problem and begin the exploration of the extragalactic universe was Edwin Hubble, the most famous astronomer of the 20th century and the namesake of the space telescope.

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Hubble had the good fortune to join the Mount Wilson Observatory essentially at the same time that the new 100-inch telescope came online in 1919. Hubble set his sights on working on the spiral nebula problem. He focused on the Great Spiral Nebula in Andromeda (M31)—what we today call the Andromeda Galaxy—and he eventually realized he could identify Cepheid variables in M31. As a result, he showed that the Andromeda Galaxy is much further away than the size of the Milky Way itself. Essentially, what Hubble showed is that spiral nebulae are island universes. He transformed our understanding of the size of the universe.

The Sombrero Galaxy (M104) is one of the 20 brightest galaxies in the sky. The Hubble image of the Sombrero Galaxy provides a spectacular close-up view of this nearly edge-on spiral, with its pronounced central bulge and tightly wound spiral arms. The very bright nucleus harbors a **black hole** of a billion solar masses. We know this because the spectrographs on the HST determined that the central stars in this galaxy are rotating rapidly around something that must be very small and very massive, and only a black hole fits that description. A black hole is essentially an object that's so massive and so compact that its gravity prevents light from escaping. One of the key discoveries made from studying galaxies with Hubble and with ground-based telescopes is that such supermassive black holes are common at the centers of large galaxies. The Milky Way also has a massive black hole at its center.

Today, using the space telescope that bears Hubble's name, astronomers are studying nearby galaxies, such as the Sombrero, in unprecedented detail and charting ever more distant galaxies. By studying these galaxies in detail, we're acquiring new knowledge about supermassive black holes and star formation. ■

Important Terms

black hole: A region of severely curved space around a collapsed stellar core where not even light can escape.

Cepheid variable: A type of pulsating star with a period-luminosity relation that is useful in determining distances to the star's host galaxy.

Suggested Reading

Bartusiak, *The Day We Found the Universe*.

Christianson, *Edwin Hubble*.

Waller and Hodge, *Galaxies and the Cosmic Frontier*.

Questions to Consider

1. Imagine that the Earth and HST were relocated to a position in the inner disk of the Sombrero Galaxy. How would the Sombrero galactic halo appear from this position? How would the Milky Way Galaxy appear to HST?

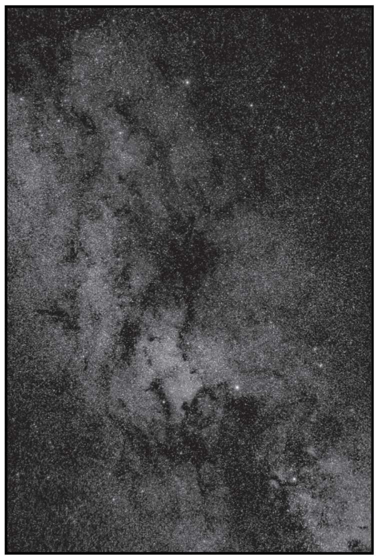
2. Suppose that the Sombrero Galaxy was the nearest galaxy to the Milky Way at its distance of 28 million light-years. Would Henrietta Leavitt have discovered the Cepheid period-luminosity relation? Would Edwin Hubble have solved the spiral nebula problem?

Hubble's View of Galaxies Near and Far

Lecture 8

The galaxies that are farther away are moving away faster. The way we can understand this in terms of our universe and an expanding universe is that the larger the distance of the galaxy from us, it takes longer for the photon to get here, and the longer it takes for the photon to get here, the longer the photon is traveling through this expanding space.

After Edwin Hubble discovered the vast cosmos of galaxies beyond the Milky Way, he began investigating the velocities of the galaxies. Initial velocity measurements of a few galaxies by others indicated that most were moving away from the Milky Way, some at high speed but with no clear pattern. In his most astonishing discovery, Hubble subsequently showed that there was a simple pattern, and it was tied directly to the galaxy distances in the form of an expanding universe.



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Edwin Hubble's definitive finding of a vast cosmos of galaxies beyond the Milky Way was an achievement that would be the pinnacle of any astronomer's career.

Hubble's greatest discovery built upon the work of Vesto Slipher, who used the spectrograph to make the first serious study of galactic velocities in 1912 at Lowell Observatory in Flagstaff, Arizona. A spectrograph takes incoming starlight, breaks it up into a spectrum of colors, then records the brightness of this starlight in each color in wavelengths. These wavelengths evidence the **Doppler effect**: If a star is moving away from you, the wavelengths are redder, or redshifted; if a star is moving toward you, the wavelengths are blueshifted. After obtaining spectra for 14 nebulae, Slipher noted that all the nebulae

exhibited redshifts and all seemed to be moving away. This observation seemed to favor the idea that the nebulae were not part of this galaxy, but lacking the distances to those nebulae, nothing certain could be said.

Later, Hubble published his work on the Andromeda Galaxy and settled the question of where the spiral nebulae were once and for all; then, Hubble followed up this work by measuring the distances to other nearby galaxies whose velocities had been determined by Slipher. In 1929, he published a landmark paper showing that there was actually a simple linear relationship between the velocities and distances of 24 nearby galaxies. According to this relationship, if the velocity is doubled, the distance is doubled.

Hubble, with his access to the 100-inch telescope at Mount Wilson, began measuring the distances and velocities of galaxies beyond Slipher's nearby sample. By 1936, he and his assistant, Milton Humason, had pushed this relationship between velocity and distance out to velocities of 20,000 kilometers per second, and they found that it held true for distances beyond 100 million light-years. There was now no doubt that this was a large-scale effect, and the relationship between the velocities and distances of galaxies became known as **Hubble's law**.

With Hubble's law and the observation that all the galaxies appear to be moving away from the Milky Way, the simple explanation is that we live in an expanding universe.

With Hubble's law and the observation that all the galaxies appear to be moving away from the Milky Way, the simple explanation is that we live in an expanding universe. The most challenging aspect of refining Hubble's law and extending its reach has been the accurate determination of galaxy distances further and further away. The value of **Hubble's constant**—the constant of proportionality between the velocity of a galaxy and its distance—was uncertain for many years after Hubble's initial work. Determining this constant was made a key project of the HST, and by 2009, it had succeeded to a significant degree, finding that Hubble's constant is equal to 74.2 +/– 3.6 kilometers per second per megaparsec.

Images of such galaxies as NGC 3370 were key to enabling Hubble to map the expansion of the universe with unprecedented precision out to vast distances. Even at the great distance of NGC 3370, the Hubble could resolve the Cepheids and, using them, determine the distance of NGC 3370 to be 98 million light-years. This is far beyond the capabilities of ground-based telescopes, which are typically limited to 20 to 30 million light-years.

There's another reason this galaxy is so important: A Type Ia supernova was seen in NGC 3370 in 1994. This kind of supernova occurs when a white dwarf in a close binary star system explodes as a result of taking on additional mass from the larger star. At maximum brightness, these stars are the most luminous kind of supernovae, with the potential of being detected at distances of billions of light-years; also at maximum brightness, they seem to have the same luminosity. We know this because the galaxies in which some of these supernovae have occurred contain Cepheids with well-measured distances. As a result, Type Ia supernovae have become a means to measure very great astronomical distances.

This development has been vital to establishing an accurate value for Hubble's constant, and using this accurate value, Hubble has shown that the cosmos is actually expanding faster now than it was billions of years ago. This finding stunned astronomers in the 1990s; if anything, they had expected the universe's expansion to be slowing down over time. The source of this observed acceleration in the expansion of the universe is completely unknown, although astronomers believe that energy associated with the fabric of space itself is driving the acceleration—the mysterious **dark energy**. ■

Important Terms

dark energy: The mysterious energy believed to be driving the observed acceleration in the expansion of the universe.

Doppler effect: The wavelength shift in the spectrum of a light source as that source moves toward or away from an observer.

Hubble's constant: The constant of proportionality between the redshift velocities of galaxies and their distances.

Hubble's law: The linear relationship between the redshift velocities of galaxies and their distances that is indicative of an expanding universe.

Suggested Reading

Bartusiak, *The Day We Found the Universe*.

Christianson, *Edwin Hubble*.

Kirshner, *The Extravagant Universe*.

Questions to Consider

1. Why are Type Ia supernovae a more reliable standard candle than Type II supernovae?

2. How have HST observations of galaxies both near and far been crucial to the discovery of dark energy?

The Antennae Galaxies—A Cosmic Collision

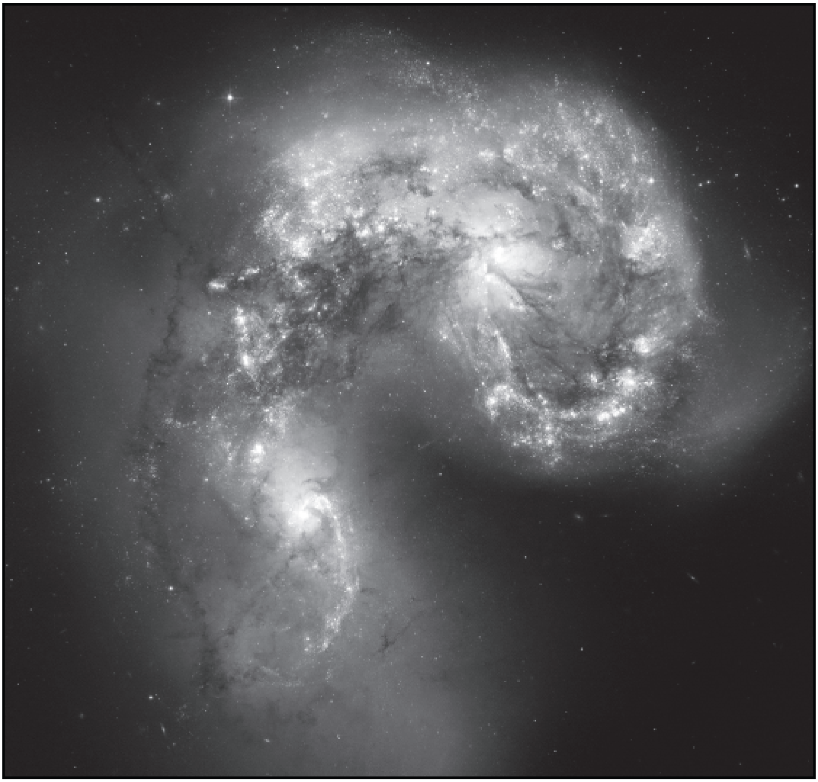
Lecture 9

One of the really amazing findings about our galaxy over the past 30 years is a significant fraction of stars in our galactic halo exhibiting these kinds of streaming motions that indicate they were once part of smaller galaxies, and these small galaxies have been disrupted by the gravity of the Milky Way into these streams. The Milky Way has, over time, captured a number of small galaxies and shredded them.

Only in the space between the clusters of galaxies and the isolated field galaxies between the clusters does the concept of an expanding universe apply. As the galaxies within a cluster orbit their collective center of mass, there will inevitably be close interactions that may result in collisions. Hubble has imaged a number of these cosmic train wrecks. The most spectacular nearby example is that of the Antennae Galaxies, which represent a snapshot in time of an ongoing collision between two spirals that were once similar to the Milky Way. Another nearby example, the Sagittarius Dwarf Elliptical Galaxy, is close enough to the Milky Way to strongly feel its gravitational influence; the tidal forces associated with that intense gravity are pulling this little dwarf galaxy apart, leaving a stream of stars through the halo associated with the galaxy.

This interaction will be significant, because both Andromeda and the Milky Way have similar large masses—hundreds of billions of stars in each galaxy interacting with one another, plus all the gas and dust in both galaxies interacting.

A much more dramatic event awaits our galaxy in about 2 billion years when the Andromeda Galaxy begins to interact with the Milky Way. Andromeda is one of the few galaxies measured by Vesto Slipher that actually exhibited blueshifts. This interaction will be significant, because both Andromeda and the Milky Way have similar large masses—hundreds of billions of stars in each galaxy interacting with one another, plus all the gas and dust in both galaxies



NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration. Acknowledgment: B. Whitmore (Space Telescope Science Institute).

As galaxies within a cluster orbit their collective center of mass, there will inevitably be close interactions that may result in collisions. The most spectacular nearby example is that of the Antennae Galaxies. These galaxies are a snapshot in time of an ongoing collision between two spirals that were once similar to the Milky Way.

interacting. This is a much more complicated problem to understand than the capture of a small galaxy by a large one.

Such complicated problems are a focus of computational astrophysics, which uses complex calculations to understand the interactions between galaxies. A number of these calculations have focused on the anticipated collision between Andromeda and the Milky Way, and they find that the **elliptical galaxy** that results will have far less gas than the two spirals had originally.

By smashing a number of the gas clouds in the two galaxies together so violently, the collision will ignite the formation of many millions of stars; the result will be a starburst.

How likely is this simulation? A key uncertainty here is the velocity of Andromeda across our line of sight. Remember, the Doppler effect gives us only that component of velocity toward us or away from us. If Andromeda is moving rapidly this way, then it might not hit us at all. The best we have been able to do with estimating Andromeda's movement across our line of sight is to say that its velocity is probably equal to or less than its velocity coming toward us. It's possible, then, that there might not be a head-on collision, just a glancing blow. The collision may not be as dramatic as the simulations have shown. However, even a glancing blow could have a significant effect on the two galaxies.

Computer simulations of galaxy interactions are developed and tested using observations of collisions in progress. As one of the nearest examples of an ongoing collision between two spirals, the Antennae Galaxies provide a wonderful snapshot into the potential future of the Milky Way and Andromeda. A ground-based, wide-field view of the Antennae shows long tidal tails of stars, from which the interacting galaxies earned their name. Seeing these tidal tails on the Antennae Galaxies gives us more confidence in the software simulations; this is something we might expect when Andromeda and the Milky Way interact. Moreover, the high resolution of the HST can identify the individual star clusters that form; indeed, there are large numbers of massive, million–solar-mass star clusters amongst this glow in the collision between these two galaxies.

Hubble's discovery of such interacting galaxies very far away reveals that they were more common in the distant past when the universe was a smaller place. Hubble continues to rapidly expand the detailed image inventory of distant interacting galaxies. One of the most amazing images appears on a poster that shows 59 such interactions between galaxies. We see head-on collisions; we see glancing blows; and we see them in different epochs of their interaction. Some are just starting, and some are well along. These Hubble images are vital to a better understanding of the future interaction between the Milky Way and Andromeda. Although each colliding galaxy

photo is in some way unique and only a snapshot in time of a lengthy, dynamic process, the sheer quantity of detailed images provided by Hubble affords astronomers an unparalleled opportunity to test and refine their simulations across the timeline of galaxy interactions. Hubble has made a dramatic difference here. ■

Important Term

elliptical galaxy: A gas-poor, elliptically shaped system of up to 500 billion typically old stars.

Suggested Reading

Christensen, de Martin, and Shida, *Cosmic Collisions*.

Loeb and Cox, "Our Galaxy's Collision with Andromeda."

Questions to Consider

1. How might we determine whether a nearby star is a native of the Milky Way or an immigrant from a cannibalized dwarf galaxy?

2. Based on the HST image alone, what are the features that lead us to conclude that the Antennae Galaxies are the result of two colliding spirals rather than two colliding ellipticals?

Abell 2218—A Massive Gravitational Lens

Lecture 10

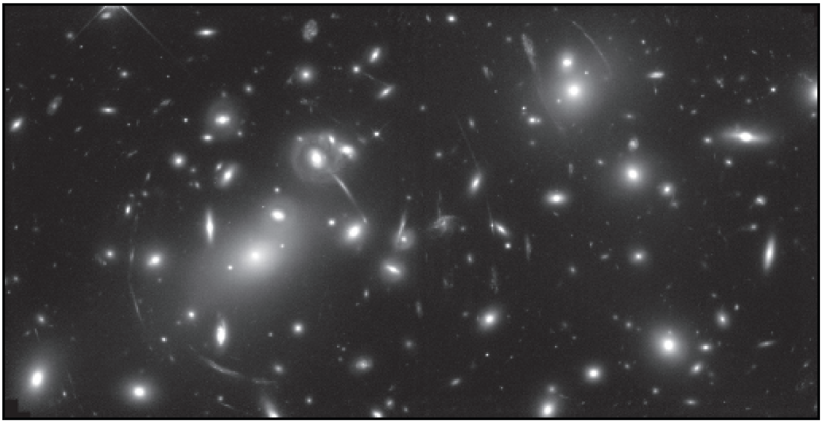
Hubble also has the remarkable achievement that it's actually imaged the double Einstein ring, which is an alignment of not just two but three galaxies along the sightline.

One of the most fascinating phenomena observable in the night sky with a telescope is a **gravitational lens**. Such a lens is actually an object, or cluster of objects, whose mass is large enough to curve the surrounding space to such a degree that the images of background objects are affected. The idea of curved space sounds like something right out of science fiction, but it is real and its effects can be observed in stunning detail with Hubble.

As part of his general theory of relativity, Albert Einstein developed the idea that gravity is a manifestation of the curvature of space in the vicinity of massive objects. If light is coming toward us in the direction of the Sun from a star beyond the Sun, it will be curved by the curvature of space associated with the mass of the Sun. In 1916, Einstein predicted that starlight right on the edge of the Sun should appear shifted 1.7 arc seconds from its true sky position. During an eclipse in 1919, British astronomers confirmed this prediction.

The simplest case of a gravitational lens occurs when the observer, the lens, and the background object are all perfectly aligned. In this case, "perfectly aligned," means within much less than 1 arc second. The result of this alignment is an **Einstein ring**. The space curvature around a gravitational lens spreads the image of the background object into a ring of light or into arcs as partial rings. About 50 partial to full Einstein rings have actually been discovered optically. The high-resolution images obtained with Hubble are absolutely key to understanding the physics associated with these Einstein rings.

The most spectacular cases of gravitational lensing involve distant rich clusters of galaxies. The Hubble image of the rich galaxy cluster Abell 2218,



NASA, Andrew Fruchter, and the ERO Team [Sylvia Baggett (STScI), Richard Hook (ST-ECF), Zoltan Levay (STScI)] (STScI).

The Hubble image of the massive cluster of galaxies Abell 2218 shows a number of thin, arc-like features that seem to partially encircle the large elliptical at the cluster core. It turns out that the arcs are galaxies far beyond Abell 2218, whose images have been amplified and distorted by the intervening space curvature associated with this cluster's gravitational field.

2 billion light-years away, reveals about 80 bright cluster galaxies and more than 100 gravitationally lensed, arc-like images of the background galaxies. When we study some of the arcs in detail, we note that some of the faintest arcs are very red, indicating that they are likely to be a great distance at high redshift. Indeed, in 2002, it was possible to obtain brown-based spectra of two of the faint red spots in the Hubble image, and they yielded a very high redshift. The galaxy responsible for these two red spots was 13 billion light-years away and actually much smaller than the Milky Way. The lensing provided by Abell 2218 brightened it by a factor of 30. Without the brightness boost by the gravitational lensing and the sharp eye of the HST to see these thin arcs, these galaxies would have been almost impossible to detect.

Dark matter is matter that interacts with visible matter through gravity but not through electromagnetic forces—not through emitting or absorbing photons. We can't "see" it, but we can sense that it's present through such effects as gravitational lensing.

The lensing mass calculated for Abell 2218 is about 10 times greater than the mass in the stars and the gas, and that holds true not just for Abell 2218 but for other clusters that have been studied through gravitational lensing. What this tells us is that most of the mass in Abell 2218 must be **dark matter**. Dark matter is matter that interacts with visible matter through gravity but not through electromagnetic forces—not through emitting or absorbing photons. We can't "see" it, but we can sense that it's present through such effects as gravitational lensing. Hubble observations of gravitational lenses in other galaxy clusters continue to provide new clues about the character of dark matter.

It has been known since the 1970s that the dark matter is likely to be common in **spiral galaxies**, based on the rotational velocities of their outer stars. The original expectation was that toward the edge of a spiral galaxy, there should be less mass because we see fewer stars and the velocity of those stars should be less, just as the outer planets in the solar system orbit more slowly than the inner ones. But we actually observe a constant velocity or a slow increase out to distances where we don't even see stars in the galaxy. These "flat rotation curves" are best understood as resulting from a dark matter halo that extends far beyond the optical galactic disk and has much more mass than the visible matter in the disk. ■

Important Terms

dark matter: The dominant, unknown constituent of matter in the universe that interacts with visible matter gravitationally but not through electromagnetic forces.

Einstein ring: The simplest case of a gravitational lens, in which the observer, lens, and background object are perfectly aligned.

gravitational lens: An object (or cluster of objects) whose mass is large enough to curve the surrounding space to a degree at which distortions are produced in the images of background objects.

spiral galaxy: A gas-rich, disk-shaped system of young and old stars with ongoing star formation in its characteristic spiral arms.

Suggested Reading

Freeman and McNamara, *In Search of Dark Matter*.

Gates, *Einstein's Telescope*.

Questions to Consider

1. How might we determine whether an odd-shaped galaxy that appears on the sky within a rich galaxy cluster is a gravitationally lensed image of a much more distant galaxy?

2. If the Milky Way has a massive halo of dark matter, why doesn't HST see gravitationally lensed images of galaxies all over the sky?

The Hubble Ultra Deep Field

Lecture 11

Indeed, there are over three times as many galaxies in the Ultra Deep Field than the number of naked-eye stars in the entire night sky. Furthermore, all of these galaxies fill a sky area that's 60 times less than that of the full Moon.

Following Edwin Hubble's discovery of the expanding universe, astronomers developed theories to explain the phenomenon. The Big Bang idea propounds a singular origin in the past for everything and expects that, over time, galaxy density will decrease. As the galaxies pull away from one another, the voids will just keep expanding. Until 1965, no evidence definitively favored this idea, but then Arno Penzias and Robert Wilson serendipitously discovered the **cosmic microwave background radiation** and essentially settled the debate in favor of the Big Bang. At Bell Labs in Holmdel, NJ, Penzias and Wilson were testing microwave receivers for satellite communication and detected microwave background "noise" that seemed to come from everywhere. At about the same time, it just so happened that astrophysicists at Princeton University were thinking that it might be possible to detect remnant radiation from the time shortly after the Big Bang in the form of a microwave background across the sky. These two scientific groups published joint papers in the *Astrophysical Journal* in 1965, and Penzias and Wilson were later awarded the Nobel Prize for discovering the signal of the Big Bang.

In the standard Big Bang model, the microwave background dates back 13.7 billion years; it is the redshifted remnant from a time when the entire universe was small, dense, and hot like a star. The universe was a vast plasma of photons bouncing off electrons. Since then, with the expansion of the universe, these photons have redshifted by a factor of 1,000 from optical to microwave wavelengths. Since Penzias's and Wilson's discovery of the microwave background radiation, a long series of microwave background measurements of increasing sensitivity have been made in an effort to pick up tiny temperature fluctuations in the radiation across the sky. These temperature fluctuations reflect small matter fluctuations in the universe

that could indicate galaxy formations long ago. The most sensitive all-sky microwave background measurements to date, those taken by the Wilkinson Microwave Anisotropy Probe, have revealed temperature variations of 1 part in 100,000 across the sky. Computational astrophysics uses these data to create models of the early universe that are tweaked as more data become available.

Can we look back far enough with our telescopes to see galaxies actually evolving over time, as we would expect in a Big Bang model? In other words, if the Big Bang model is indeed correct, the universe should evolve over time, and the most distant galaxies should be morphologically distinct from the present-day galaxy population. Can the Hubble's exceptional sky resolution resolve the most distant galaxies to determine whether their morphologies differ from those of the spiral and elliptical galaxies that we see today? As it turns out, the 1996 Hubble Deep Field image showed that the most distant galaxies tend to be peculiar, which is consistent with the evolving universe expectations of the Big Bang model.

[T]he 1996 Hubble Deep Field image showed that the most distant galaxies tend to be peculiar, which is consistent with the evolving universe expectations of the Big Bang model.

In 2004, an even more ambitious effort, the Ultra Deep Field, captured objects 4 billion times fainter than the faintest object you can see in the night sky with your eye. When we study this image in detail, we see 10,000 galaxies spread out over a sky area equivalent to only about 1.7 percent of the full Moon sky area. If you assume this is an average galaxy density, then the entire sky would yield a population of 130 billion galaxies in the observable universe. Like the Hubble Deep Field image, close-ups of the Ultra Deep Field reveal many galaxies with asymmetric morphologies; in particular, 165 tadpole-shaped galaxies tend to be appreciably smaller than the Milky Way, suggesting that galaxies grew bigger through frequent collisions. The reddest Ultra Deep Field galaxies are the most distant dwarf galaxies, and they date back to a time less than 1 billion years after the Big Bang. Their star formation rates are about 10 times greater than those of nearby galaxies, which makes sense. If there

were numerous collisions going on in the early universe, we'd expect large starbursts to occur, even in interactions among small galaxies.

What about the very first stars and the very first galaxies? If we can push Hubble any further, can we see those? Unfortunately, the very first stars and galaxies in the universe are probably too faint for Hubble. Their light is probably redshifted into the infrared part of the spectrum, where Hubble is not sensitive. One of the things that the Hubble Ultra Deep Field shows us is that even Hubble has its limits; we can't see all the first stars and first galaxies in the universe. ■

Important Term

cosmic microwave background (CMB) radiation: The redshifted radiation from a very early time (380,000 years after the Big Bang) when the expanding universe transitioned from its hot, dense, bright origin to a cooler, transparent state.

Suggested Reading

Beckwith et al., "The Hubble Ultra Deep Field."

Gardner, "Finding the First Galaxies."

Singh, *Big Bang*.

Questions to Consider

1. What would the Hubble Ultra Deep Field look like in a Steady State universe?

2. What are all the factors involved in choosing a sky region for the deepest possible image of the most distant galaxies?

Hubble's Legacy and Beyond

Lecture 12

The Kepler Space Telescope will be able to detect Earth-size orbits, those orbits that have a period of a year or more. ... The Kepler telescope will answer a question that humanity has asked for thousands of years: Are Earth-sized planets rare or common around other stars in the galaxy?

Hubble is not capable of directly imaging an Earth-size or Jupiter-size planet in an Earth-size or Jupiter-size orbit around any solar-type star at optical wavelengths. Nevertheless, we are living in the golden age of **exoplanet** discovery right now. Since the early 1990s, more than 400 exoplanets have been discovered indirectly through spectroscopy on ground-based telescopes. The method for finding exoplanets uses our old friend the Doppler effect. You point a large telescope with a very efficient, high-resolution spectrograph at a star and you study it for very tiny velocity shifts. These shifts may be due to an orbiting planet tugging on the star, occasionally pulling it toward us and then away from us. The indirect gravitational effect of wobbling will be picked up as tiny blue and red shifts corresponding to the period of the planet's orbit.

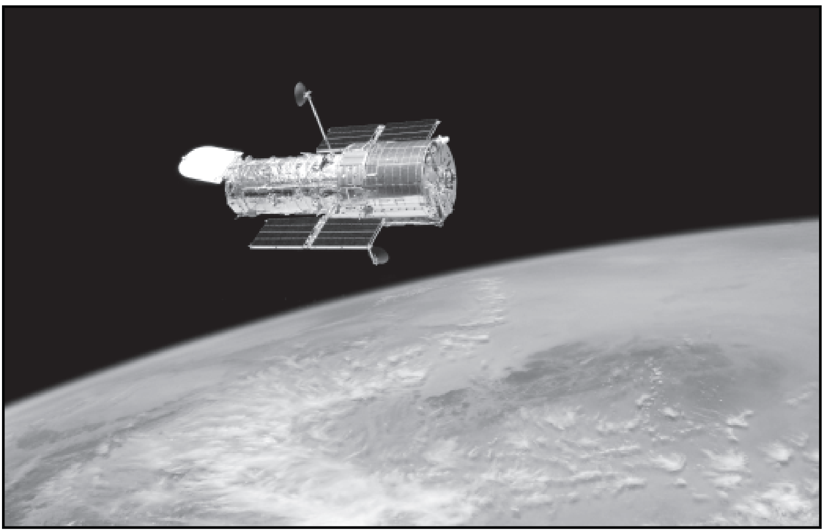
The Doppler method has been amazingly successful: Planets have been found around about 15 percent of the 2,000-some solar-type stars surveyed. A little more than 20 years ago, the only planets we knew about in the entire galaxy were in our solar system. Another indirect approach to detecting planets is to study stars for planets with edge-on orbits: As the planet passes in front of the star, it dims the light of the star. This method has already had a great deal of success from the ground: More than 40 Jupiter-sized planets have been detected in close orbits through this method.

Although Hubble has not imaged an Earth or a Jupiter in comparable orbits around another star, it has optically detected an exoplanet in observations released in 2008. The targeted star was Fomalhaut, somewhat younger and hotter than the Sun and 25 light-years away. By comparing the 2004 and 2006 data, Hubble astronomers found a small dot, a point of light, just inside the dust belt around Fomalhaut. This dot, a billion times fainter than the star,

is an exoplanet. Only because this exoplanet is three times more massive than Jupiter and very far away from its host star could Hubble find it. The direct detection of the Fomalhaut exoplanet is an impressive example of the limits of Hubble and the need for new technology to image less massive exoplanets much closer to their host stars.

The next big step in imaging extrasolar planets will take place in 2014 when NASA launches the successor to Hubble, the James Webb Space Telescope. The Webb telescope will have a mirror much bigger than that of Hubble (6.5 meters as opposed to 2.4), its optics and instruments will be optimized for observations at infrared wavelengths, and (to best study this infrared-wavelength light) its orbit will be outside the Earth's orbit. What that means is if something goes wrong with Webb, there's no way to fix it.

Until the Webb telescope is launched and, perhaps, afterward, Hubble will continue to explore the cosmos. The space shuttle servicing mission to



NASA.

There will be no further upgrades or repairs of Hubble. What is the eventual fate of Hubble? Sometime beyond 2020, its orbit will decay, and if nothing is done, it will burn up in the atmosphere—at least most of it will, but some pieces could make it to the ground.

Hubble in 2009 was a fantastic success. New instrumentation was installed; the Space Telescope Imaging Spectrograph, which failed several years ago, was repaired and is working well now as a result of this servicing mission; and the **Advanced Camera for Surveys** was also restored almost to its full functionality. In addition to working on these instruments, the astronauts on the servicing mission performed important basic maintenance on the telescope. The scientific lifetime of Hubble has now been extended for at least five years and maybe even a decade.

However, the bad news is that there will be no further upgrades or repairs of Hubble. By retiring the space shuttle fleet, NASA will no longer be able to fix Hubble. Sometime beyond 2020, its orbit will decay and it will burn up in the atmosphere—at least most of it will, but some pieces could make it to the ground. Concerns about that led the astronauts of the 2009 servicing mission to attach a docking port to Hubble, so that at some point in the future, before its orbit decays, a robotic spacecraft might be sent up, attach itself to Hubble, and de-orbit Hubble into the ocean safely.

By retiring the space shuttle fleet, NASA will no longer be able to fix Hubble. Sometime beyond 2020, its orbit will decay and it will burn up in the atmosphere.

Until its eventual demise, all of Hubble's observations will continue to be saved in its vast public data archive at http://archive.stsci.edu. This archive has been a tremendous resource for researchers; indeed, many research papers have been based on the archive data alone. But beyond the raw data, Hubble's legacy will be the spectacular images that have not only helped researchers to rewrite the textbooks but have also stimulated students of all ages to learn more about the universe. ■

Important Terms

Advanced Camera for Surveys (ACS): The third-generation camera installed onboard HST during the 2002 space shuttle servicing mission.

exoplanet: A planet outside the solar system.

Suggested Reading

Boss, *The Crowded Universe*.

Gardner, “Finding the First Galaxies.”

Mayor and Frei, *New Worlds in the Cosmos*.

Questions to Consider

1. What would be the implications for exoplanet studies and future NASA missions if the Kepler Space Telescope finds that Earth-sized exoplanets are rare?

2. Which HST images will have the most long-lasting scientific and aesthetic impact?

Glossary

Advanced Camera for Surveys (ACS): The third-generation camera installed onboard HST during the 2002 space shuttle servicing mission.

asteroid: Member of a class of rocky objects orbiting the Sun, ranging in size from meters to hundreds of kilometers.

baryon: Member of a class of particles, including protons and neutrons, that make up most of the matter in the visible universe.

Big Bang universe: An evolving universe that had a singular origin in time.

black hole: A region of severely curved space around a collapsed stellar core where not even light can escape.

Cassegrain telescope: A telescope in which incoming starlight is reflected off a primary mirror to a secondary mirror that then reflects it back through a small central hole in the primary mirror to an eyepiece or instrument behind the primary.

Cepheid variable: A type of pulsating star with a period-luminosity relation that is useful in determining distances to the star's host galaxy.

comet: A kilometer-sized object of ice and rock that produces a visible tail of vapor and dust as it approaches the Sun during the course of its orbit.

cosmic microwave background (CMB) radiation: The redshifted radiation from a very early time (380,000 years after the Big Bang) when the expanding universe transitioned from its hot, dense, bright origin to a cooler, transparent state.

dark energy: The mysterious energy driving the observed acceleration in the expansion of the universe.

dark matter: The dominant, unknown constituent of matter in the universe that interacts with visible matter gravitationally but not through electromagnetic forces.

Doppler effect: The wavelength shift in the spectrum of a light source as that source moves toward or away from an observer.

Einstein ring: The simplest case of a gravitational lens, in which the observer, lens, and background object are perfectly aligned.

electromagnetic radiation: Commonly referred to as "light" at optical wavelengths, this radiation is due to oscillating electric and magnetic fields.

elliptical galaxy: A gas-poor, elliptically shaped system of up to 500 billion typically old stars.

emission nebula: A glowing cloud of interstellar gas heated by the ultraviolet light of a nearby hot star.

exoplanet: A planet outside the solar system.

globular star cluster: A densely packed, spherical cluster of up to a million old stars typically found in the halos of galaxies.

gravitational lens: An object (or cluster of objects) whose mass is large enough to curve the surrounding space to a degree at which distortions are produced in the images of background objects.

Hertzsprung-Russell (HR) diagram: A diagram comparing the temperatures and luminosities of stars that is useful in charting their evolution over time.

Hubble's constant: The constant of proportionality between the redshift velocities of galaxies and their distances.

Hubble's law: The linear relationship between the redshift velocities of galaxies and their distances that is indicative of an expanding universe.

interstellar dust: Submicron-sized interstellar particles of carbon, oxygen, and silicon compounds that are effective in attenuating background starlight.

interstellar molecular cloud: An interstellar cloud of gas and dust that is dense enough to form molecules (and sometimes stars) and block the optical light of background stars.

light-year: The distance (6 trillion miles) that light travels in one year.

main sequence star: A star that is powered by the nuclear fusion of hydrogen into helium in its core.

Near-Earth Object (NEO): A nearby asteroid whose orbit intersects that of Earth.

neutrino: An elementary particle of very low mass produced in nuclear reactions, such as those in the solar core and Type II supernovae.

neutron star: The collapsed core remnant of a Type II supernova; it typically has a mass of about 1.5 solar masses within its radius of 10 kilometers.

photon: The particle that carries electromagnetic radiation (light) with wavelike characteristics.

planetary nebula: The short-lived nebula (lasting for about 50,000 years) that results when a dying red giant blows off the gaseous layers surrounding its core.

pulsar: A rapidly rotating neutron star.

red giant: After a solar-type main-sequence star fuses all of its core hydrogen into helium, it evolves into this type of cooler, larger, more luminous star.

resolving power: A measure of the smallest angular separation that a telescope can resolve in an image.

seeing: A measure of the limiting resolving power for ground-based telescopic observations produced by atmospheric turbulence.

spherical aberration: An error in the shape of a lens or mirror that prevents all of the incident light from coming into focus at the same imaging point.

spiral galaxy: A gas-rich, disk-shaped system of young and old stars with ongoing star formation in its characteristic spiral arms.

standard candle: A class of objects whose luminosity is assumed to be known.

Steady State universe: A non-evolving universe whose large-scale characteristics are constant in space and time.

supergiant: After a massive main-sequence star fuses all of its core hydrogen into helium, it eventually evolves into this type of very large, very luminous, cool star.

supernova remnant: The expanding, nucleosynthetically enriched gaseous remnant of a star that has undergone a supernova explosion.

white dwarf: The final stage in the evolution of the Sun (and 99 percent of the stars in the Milky Way Galaxy); a compact, Earth-sized object radiating its remnant energy like a dying coal in a fireplace.

Wide-Field Camera 3 (WFC3): The fourth-generation camera installed onboard HST during the 2009 space shuttle servicing mission.

Wide-Field Planetary Camera 2 (WFPC2): The second-generation camera installed onboard HST during the 1993 space shuttle servicing mission.

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